A Modified Beckmann-Kirchhoff Scattering Model for Slightly Rough Surfaces at Terahertz Frequencies

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***Abstract*—The diffuse reflection of electromagnetic waves is merely dependent on the surface roughness, incident angles, complex refractive index of materials and wavelength at hand. At terahertz frequencies, diffuse reflection tends to be particularly strong due to the increased surface roughness and this causes an additional attenuation even in the specular direction of reflection. In this paper, we examine the terahertz (THz) channel from 300 GHz (0.3 THz) to 310 GHz (0.31 THz) in the presence of slightly rough surfaces ($0 < g \ll 1$) by using the approximate solutions from Rayleigh-Rice (R-R) and Beckmann-Kirchhoff (B-K) scattering theories. However, the classical Beckmann-Kirchhoff theory contains a small-angle limitation (i.e., it fails at large angles of incidence and wide scattering angles). Thus, we also endeavor to demonstrate the modified Beckmann-Kirchhoff scattering theory, an approach by Verold and Harvey, using multipath channel transfer function (CTF) dynamics for line-of-sight (LoS) and non-line-of-sight (NLoS) conditions in a simple office environment.**

Keywords*—THz communication, slightly rough surfaces, ray-tracing, Rayleigh-Rice theory, Beckmann-Kirchhoff theory.

I. INTRODUCTION

By 2020 wireless data rates up to 100 Gb/s will be on demand [1], helping to get through the struggle in progress of multimedia technology, high-speed internet, data and voice communication. It seems clear that to achieve 100 Gb/s wireless links, transmitting in the THz region of electromagnetic spectrum is vital. For instance, to transmit at 300 GHz carrier frequency is the choice of the fortune for three reasons: (i) it is five times higher than the highest frequency of 60 GHz used in wireless communications today; (ii) the atmospheric attenuation is of less extreme amounts to no more than 2.8 dB/km while falling within the spectral windows; and (iii) it procures a 47 GHz of bandwidth which is larger than the unified spectral resources globally available for all kinds of wireless systems.

Thus far, a very few ultra-broadband THz channel results based on measurements [2]- [3] have been reported. But the influence of diffuse reflection in the non-specular direction has only been considered using ray-tracing by including scattering model proposed by Beckmann [4]. It is important to notify that none of the former papers have investigated ultra-broadband channel behaviour in a realistic office environment by considering modified B-K scattering model which does not exhibit the unphysical discontinuity at wide scattering angles. Moreover, the comparison of R-R, classical and modified B-K models does not exist.

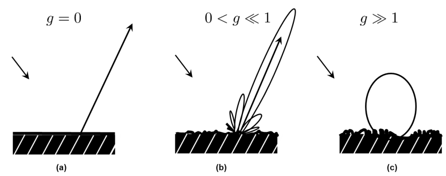

Fig. 1: The specular and diffuse reflection. The surfaces are: (a) perfectly smooth, (b) slightly rough, and (c) very rough.

This work demonstrates the ultra-broadband channel behaviour by using our self-developed ray tracing algorithm (RTA) [5] in terms of the frequency-domain channel transfer function at 3201 frequency points for f = 300...310 GHz in both LoS and NLoS scenarios. The surface scattering process for diffuse reflection has been analyzed using the most prominent analytical scattering theories such as R-R [6]- [7], B-K [8] and modified B-K theory [9]. The diffuse reflection impact from rough surfaces in the specular direction has been modeled based on R-R theory (i.e., the specular losses occur due to the diffuse reflection). However, the classical B-K model as well as modified B-K are implemented accounting for the diffuse reflection in both specular and non-specular directions. We use a commercial ray-tracer for the former whereas for the latter two we employ our RTA. The reflection/scattering pattern depending on the roughness parameter g is illustrated in Fig. 1.

II. SURFACE SCATTERING MODELS

A. *Rayleigh-Rice Model*

The R-R approach can be seen as the most rigorous analytical solution of Maxwell's equations for the limiting case of slightly rough surface. Rayleigh expressed optical smoothness by following the accurate criterion from [7] as

$$(4\pi\sigma_h \cos\Theta_i/\lambda)^2 \ll 1 \tag{1}$$

The details about the expressions σ_h, Θ_i, and λ are given at [6].

B. *Classical Beckmann-Kirchhoff Model*

The classical B-K theory is more realistic and provides more insight of the physical processes involved in the surface scattering. The classical B-K model is validated against ultra-broadband measurements at THz frequencies [4]. According to classical B-K theory, the scattering coefficient for slightly rough surface is

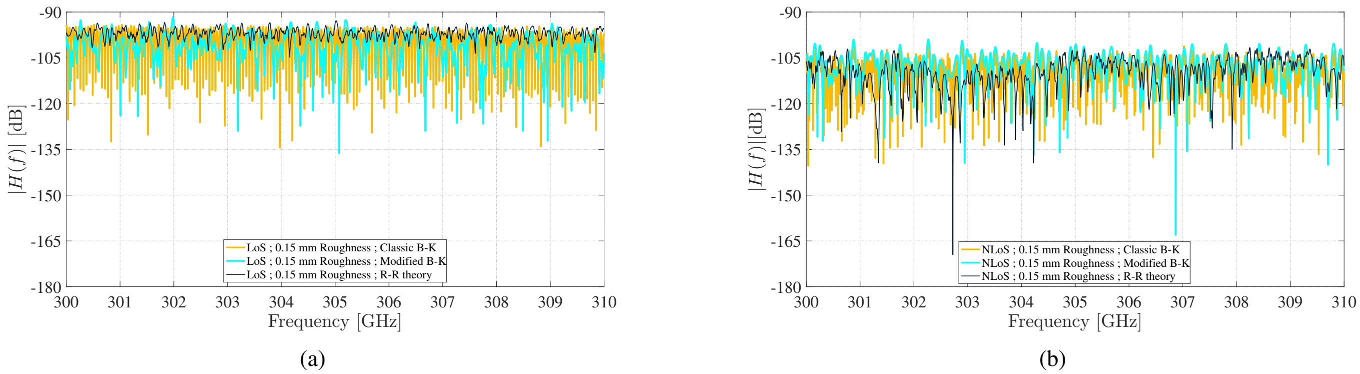

Fig. 2: Comparison of channel transfer functions between classical B-K, modified B-K and R-R models in presence of slightly rough surfaces at receiver locations (a) RX-LoS and (b) RX-NLoS.

$$\langle \rho\rho^* \rangle_{\text{slightly rough}} = \left(\rho_0^2 + \frac{\pi \ell_{cr}^2 F^2 g}{A} \, e^{-\frac{v_{xy}^2 \ell_{cr}^2}{4}} \right) e^{-g} \tag{2}$$

The geometrical factor, a function of incident and scattered angles is

$$F = \frac{1 + \cos(\Theta_i)\cos(\Theta_r) - \sin(\Theta_i)\sin(\Theta_r)\cos(\Theta_s)}{\cos(\Theta_i)(\cos(\Theta_i) + \cos(\Theta_r))} \tag{3}$$

The details about the expressions ρ_0, ℓ_{cr}, v_{xy}, A, Θ_r, Θ_s and g are given at [8, p. 88].

C. *Modified Beckmann-Kirchhoff Model*

A modified B-K theory is attained by replacing the geometrical factor (F-factor squared) used by Beckmann with the $\cos(\Theta_i)$ in Lambert's cosine law, we get

$$\langle \rho\rho^* \rangle_{\text{slightly rough}} = \left(\rho_0^2 + \frac{\pi \ell_{cr}^2 K g}{A} \, e^{-\frac{v_{xy}^2 \ell_{cr}^2}{4}} \right) e^{-g} \tag{4}$$

The renormalization constant K in this reformulation of scalar diffraction theory is given by the following expression

$$K = \frac{\displaystyle\int_{\alpha=-\infty}^{\infty} \int_{\beta=-\infty}^{\infty} L(\alpha, \beta - \beta_0) d\alpha \, d\beta}{\displaystyle\int_{\alpha=-1}^{1} \int_{\beta=-(1-\alpha^2)^{\frac{1}{2}}}^{(1-\alpha^2)^{\frac{1}{2}}} L(\alpha, \beta - \beta_0) d\alpha \, d\beta} \tag{5}$$

The details about the variables used in (5) are given at [9].

III. RESULTS AND CONCLUSIONS

Fig. 2 depicts the CTF results for the respective R-R, classical B-K and modified B-K models for Fig. 3 scenarios. We refer to author's separate publication [5] for the detailed description of the scenario, the ray-tracing algorithm and material parameters in order to avoid lengthening of this paper. For LoS case, the average attenuation over the whole bandwidth is 97.02 dB, 100.86 dB and 101.59 dB. Meanwhile, the standard deviation is 1.70, 5.96 and 5.29. However, for NLoS case the average attenuation is 110.09 dB, 109.90 dB and 107.95 dB and the standard deviation is 5.51, 5.46 and 5.20.

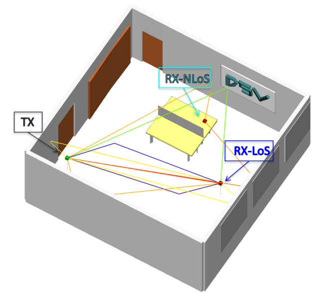

Fig. 3: 3D layout of the office room BB121 with specular propagation paths (commercial ray-tracer).

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